Appendix G

Test Method Workgroup

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Tables and Figures

I. Background

During the development of the proposed air toxic control measure (ATCM), several concerns were raised regarding the inconsistencies between test methods used to certify off-road engines and the methods commonly used by air pollution control districts to measure emissions from stationary engines. Filter-based test methods for diluted exhaust (off-road methods) have been standard for mobile and off-road engines, while stationary source methods have been the standard for new source review, compliance and permitting of stationary engines. Stationary source or compliance test methods include filterable and condensable components from undiluted exhaust. Since engine certification and verification programs typically require filter-based methods on diluted exhaust, the emission results do not correlate with and generally can not be used to compare with stationary source compliance test results used in permitting and new source reviews.

To better understand the technical issues, a Test Method Working Group was created. The goals of the workgroup were to compare the two sampling approaches and make recommendations for a test method that could be used to demonstrate compliance with the ATCM. The workgroup consisted of members from district staff representing California Air Pollution Control Officers Association (CAPCOA/District), Engine Manufacturers Association (EMA), Manufacturers of Emission Controls Association (MECA), engine manufacturers including Caterpillar and Cummins, Air Resources Board (ARB) and UC Riverside's Center for Environmental Research and Technology (UCR CE-CERT)
In addition, the workgroup addressed issues with ARB Method 5 raised by engine and control device manufactures as follows (EMA, 2002):

- Poor repeatability and test data bias.
- Inadequate accuracy and resolution, especially for the very low levels of particulate matter (PM) emitted with the use of exhaust emission control devices.
- Use of different sampling protocol that effectively result in measurement that has no defined relationship to PM data measured by engine or emission control equipment manufacturers using required certification test methods.
- PM test results that differ from real-world atmospheric particle behavior as compared to dilution measurement methods.
- Use of isokinetic sampling procedures designed for PM size ranges not found in engine emissions.
- A disconnect between the test method required to demonstrate field compliance with the methods and data originally used to develop the CA emissions standards.

In evaluating the use of off-road methods such as the International Organization for Standardization Reciprocating Internal Combustion Engines-Exhaust Emission Measurement (ISO 8178) for stationary source evaluations, the workgroup also addressed the issues of limited field availability and the impact of changing the testing methods for stationary source evaluations. (ISO/DP 8178, 1992)

The two sampling approaches have key differences including exhaust dilution, filter temperatures and condensable components, which result in emission factors that lack correlation. This difference in stationary and off-road test methods makes it difficult to utilize data generated under U.S. EPA Certification Guidance for Engines Regulated Under: 40 CFR Part 86 on-Highway Heavy Duty Engines and 40 CFR Part 89 Nonroad CI Engines (U.S. EPA Nonroad Certification) and ARB Verification Procedure, Warranty and In-Use Compliance Requirements for In-Use Strategies to Control Emissions from Diesel Engines (Verification Procedure) programs in stationary source programs. (EPA, 1999) (ARB, 2002) Furthermore, the proposed emission limits and control efficiencies included in this regulation are derived from certification and verifications that utilize filter based dilution off-road methods. The use of existing data for new or retrofitted engines could reduce the need for expensive emission testing to demonstrate compliance with the requirements of this regulation.

To compare the test methods, UCR CE-CERT performed five direct method comparison tests on stationary or portable diesel generators. Table G-1 lists test engine information and fuel sulfur content, (if available) for the test method comparison. The study included comparisons on four baseline (uncontrolled) engines and one engine retrofitted with a passive diesel particulate filter. For the retrofitted engine, both baseline and controlled PM emission factors were measured. In addition, measured control device efficiency was calculated for both test methods.

Table G-1: Test Engine Information and Fuel Sulfur Content

Engine Make/Model	Emission Controls	Test Load 100% load	Fuel (fuel sulfur ppm, if available)
Detroit Diesel 8V-92 1991 2 Stroke	Uncontrolled	2 Stroke 469 hp	CARB Diesel (374 ppm)
Cat 3406B 1991 4 Stroke	Uncontrolled	4 Stroke 422 hp	CARB Diesel (90 ppm)
Detroit Diesel Series 60 1999 4 Stroke	Uncontrolled	4 Stroke 402 hp	CARB Diesel (144 ppm)
Cat 3406 C 2000 4 Stroke	Uncontrolled	4 Stroke 466 hp	CARB Diesel
Cat 3406 C 2000 4 Stroke	Passive DPF	4 Stroke 466 hp	ULSD (< 15 ppm)

II. Test Methods

For stationary source type sampling, ARB Method 5 Determination of Particulate Matter Emissions from Stationary Sources (Method 5 or M5) was used to measure PM and ARB Method 100 Procedures for Continuous Gaseous Emission Stack Sampling (Method 100 or M100) was used to measure gaseous emissions of CO_2, CO, NOx, NO_2, total hydrocarbons (THC). (ARB, 1983) (ARB, 1983a) For the off-road test methods, ISO 8178 was used to measure PM and gaseous emissions of CO_2, CO, NOx, NO_2, total hydrocarbons (THC) and non-methane hydrocarbons (NMHC). Table G-2 provides an overview of the two test methods. Table G-3 lists the summary continuous emission monitoring systems used to sample gaseous emissions for both ARB Method 100 and ISO 8178.

Table G-2: Overview of Test Methods

Method	ARB Method 5	ISO 8178
Description	Standard stationary engine test method.	Standard test method for off-road testing, certification and verification programs.
Dilution Method	Undiluted exhaust Isokinetic	Diluted exhaust Nonisokinetic or Isokinetic allowed
Filter Component	Filter 248$\pm$25 ^oF (120$\pm$14 ^oC)	Filter Below 125^oF (52 ^oC)
Impinger Component (back half)	Impinger (~60 ^oF)	No Impinger
Field Availability	Field available	Laboratory or test bed availability Limited field availability
Engine loads	Method does not define test loads	Method defines engine test loads and speeds

Table G-3: Continuous Gaseous Sampling Analyzers

Gaseous Pollutant	Stationary Source Testing Per ARB Method 100	Off Road Testing Per ISO 8178
NOx	Chemiluminescence	Chemiluminescence
NO_2 (see Note 1)	Chemiluminescence	Chemiluminescence
CO	Non-dispersive infrared (NDIR)	Non-dispersive infrared (NDIR)
CO_2	Non-dispersive infrared analyzer	Non-dispersive infrared (NDIR)
Total Hydrocarbons	Flame ionization detector (FID) or non-dispersive infrared analyzer (NDIR)	Flame ionization detector (FID)
CH_4 and Non methane Hydrocarbons (NMHC)	Not analyzed	GC combined with FID to measure CH_4. NMHC from difference between THC and CH_4

Note 1: Speciated NO_2 is not included in either test method. It was included in this study as required by ARB Verification Procedure.

All tests were performed using a 3-mode D1 test cycle and weighting factors as specified in the ISO 8178 Part 4. Load, speed and weighting factors for the ISO 8178 D1 test cycle are listed in Table G-4.

Table G-4: Weighting Factors for ISO 8178 D1 Test Cycle

Mode number	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
Torque, %	100	75	50	25	10	100	75	50	25	10	0
Speed	Rated speed					Intermediate speed					Low idle
Type D1	0.30	0.50	0.20								

ARB Method 5

Stationary source type sampling with ARB Method 5 is performed by drawing the raw exhaust directly through a heated filter and a series of impingers in an ice bath. The total PM is composed of the filterable component caught on the filter and the condensable portion caught in the impingers. The total PM catch is itemized by weight as (1) Filter Catch, (2) Probe Catch (3) Impinger Catch and (4) Solvent Extract. The sample is drawn isokinetically from the exhaust stack and through a filter to collect filterable PM. The filter is maintained at a temperature of 248 ºF $\pm$ 25 ºF to ensure that no moisture condenses on the filter. After passing through the filter, the sample gas is drawn through a set of impingers, which are maintained below 68 ºF. After sampling for a specified time, the filter is recovered and weighted along with the weight of the particulate from the probe rinse. The filter catch combined with the probe catch (probe wash) is commonly referred to as the front half. The weight of the condensable particulate is determined by recovering the impinger liquid, extraction with methylene chloride and evaporation of the aqueous and methylene chloride extract to determine the condensable PM weight. The condensable portion remaining after evaporation of the aqueous portion is reported as the impinger catch. This portion is also commonly referred to as the inorganic portion of the backhalf. The condensable portion remaining after evaporation of the methylene chloride solvent is reported as the solvent extract. It is commonly referred to as the organic portion of the backhalf. The PM concentration is determined by dividing the weight of the total particulate catch by the volume of gas sampled.

Mass emission rates in grams/hour for particulate and gaseous emissions can be calculated with the average emission concentrations and the stack gas flowrate and moisture content. Stack gas flowrate and moisture content can be determined using ARB Methods 1 Sample and Velocity Traverses for Stationary Sources (Method 1), Method 2 Determination of Stack Gas Velocity and Volumetric Flow Rate (Method 2), Method 3 Gas Analysis for Carbon Dioxide, Oxygen, Excess Air, and Dry Molecular Weight (Method 3) and Method 4 Determination of Moisture Content in Stack Gasses (Method 4). (ARB, 1993b) (ARB, 1993c) (ARB, 1993d) (ARB, 1993e) Stack gas velocity is determined from a pitot tube measurement using ARB Methods 1 and 2 allowing computation of the total mass flow rate of diluted exhaust.

ISO 8178

Off-road type sampling is performed by diluting the exhaust with conditioned air and drawing the diluted sample through a particulate filter. PM sampling is done from diluted exhaust gas. This is achieved by turbulent mixing of exhaust gases with air in a dilution tunnel. The total PM is composed of a filterable component only. Off-road type sampling was performed using a 1992 draft version ISO 8178. This older draft version was used since it was directly incorporated by reference into the *California Exhaust Emission Standards and Test Procedures for New 1996 and Later Off-Road Compression-Ignition Engines Part II.* (ARB, 1993)

UCR CE-CERT performed dilution testing with a mobile full-flow constant volume (CVS) sampling laboratory. In the CVS method, the exhaust gases are diluted with air to maintain a constant total flow rate (air + exhaust) under all running conditions. Total exhaust (full-flow) is collected and mixed with air in the full-flow primary dilution tunnel. A sample for particulate measurement is drawn from that tunnel into a small secondary dilution tunnel, further mixed with air and collected on particulate filters maintained at or below 125 ºF. Samples for continuous gas phase measurements are drawn from the primary dilution tunnel. The volumetric flow rate is of the diluted exhaust gas is measured using a critical flow venturi and the temperature and pressure of the flow are measured allowing computation of the total mass flow rate of diluted exhaust.

III. Summary of Results

D1 emission factors were calculated using the individual modal data and D1 weighting factors for direct comparison between the ARB Method 5 and ISO 8178 emission tests. The ARB Method 5 emission factors were calculated using the filter only, the front half and the total PM (filter catch, probe catch, impinger catch and solvent extract). Table G-5 lists D1 weighted PM emission factors for ARB Method 5 components and ISO 8178 results. Figure G-1 shows the calculated emission factors for ARB Method 5 filter only, Method 5 front half and ISO 8178. Figure G-2 shows the calculated emission factors for ARB Method 5 total PM and ISO 8178. For each of the test engines, the individual modal emissions for both ARB Method 5 and ISO 8178 testing are shown in Figures G-3 through G-7.

Table G-5: Average D1 Weighted PM Emission Factors for ARB Method 5 and ISO 8178 Test Results

Engine	ARB Method 5 D1 Weighted Emission Factor			ISO 8178 D1 Weighted Emission Factor	Ratio	Ratio
	Filter only	Front Half (Note 1)	TPM		M5 Filter / ISO 8178	M5 TPM / ISO 8178
DD 8V-92	0.125	0.153 (Note 2)	0.475	0.131	0.96	3.64
DD 60 99	0.050	0.060 (Note 2)	0.187	0.057	0.88	3.31
CAT 3406B	0.092	0.112 (Note 2)	0.266	0.111	0.83	2.41
Cat 3406C Baseline	0.123	0.145	0.230	0.110	1.13	2.10
Cat 3406 C DPF Controlled	0.016	0.021	0.060	0.017	0.97	3.52
% reduction Passive DPF	86.7	85.8	74.0	84.5		

Note 1. Front Half includes probe wash and filter weight.

Note 2. Estimated based on results from CAT 3406C baseline and controlled test using average (Front Half)=1.21(Filter Only). Probe wash was not reported separately for these three engines.

Figure G-1: D1 Weighted Emission Factors - M5 Filter, M5 Front Half and ISO 8178 Filter

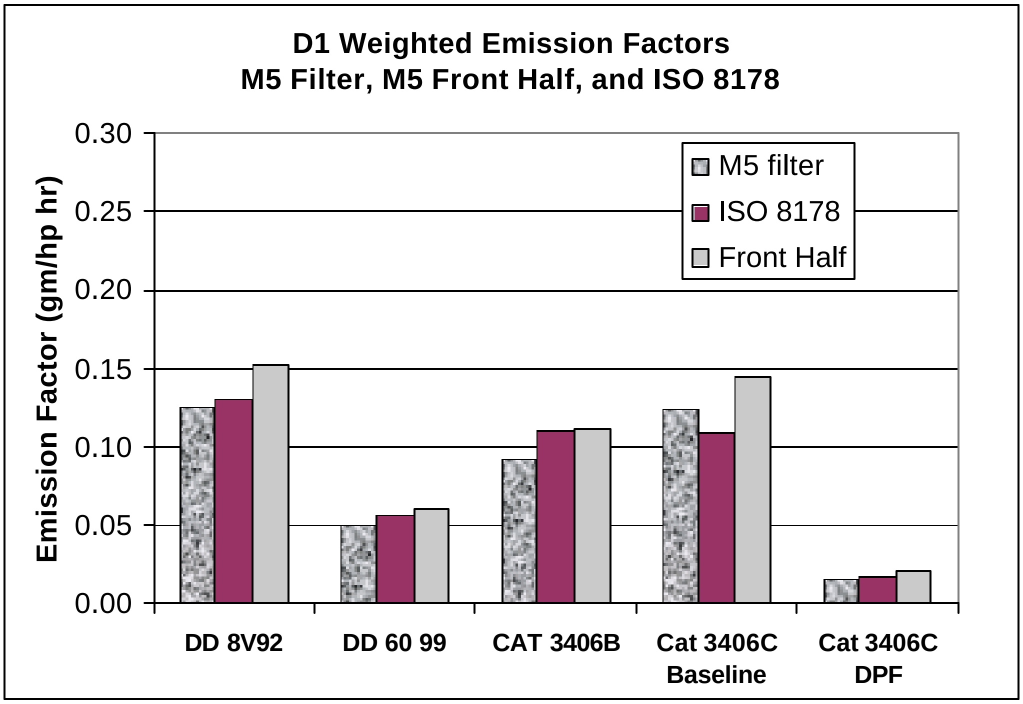
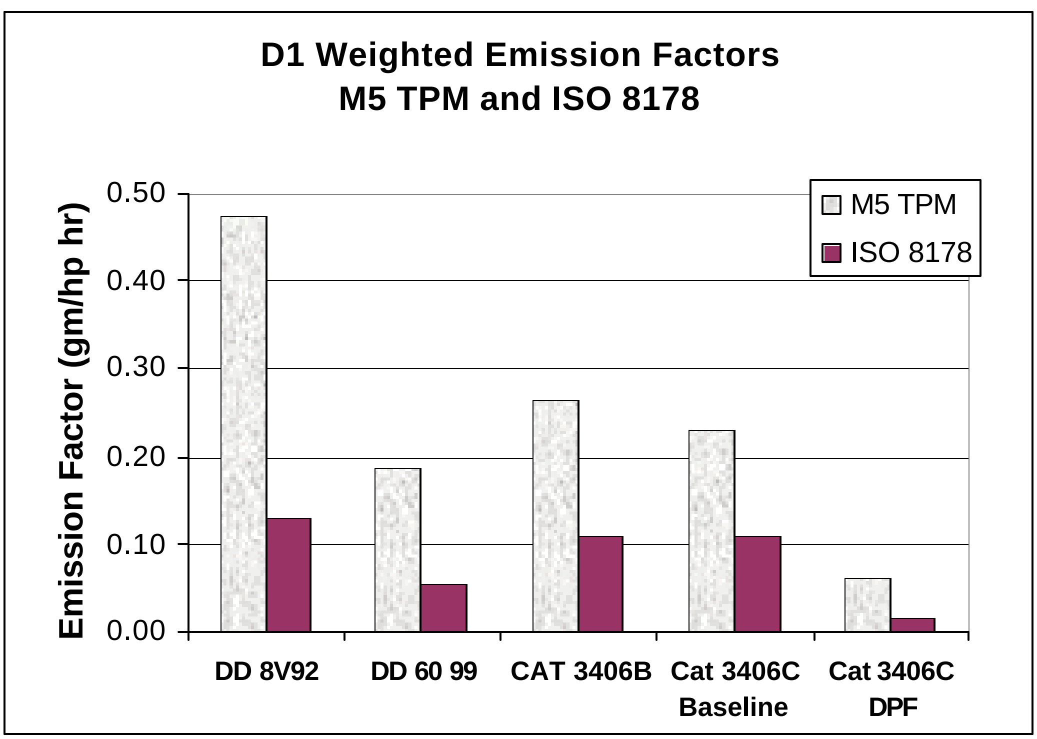


Figure G-2: D1 Weighted Emission Factors - M5 Total PM and ISO 8178 Filter



The test results indicate that total PM measured using ARB Method 5 are two to four time higher than total PM measured by ISO 8178. In comparing ARB Method 5 filter only, ARB Method 5 front half catch with ISO 8178 total PM, the results show good agreement. This data indicate that the differences in exhaust dilution and filter temperature conditions may not have as significant impact as inclusion of a condensable component, when measured gravametrically. The condensable portion can be as large as 75 percent of the total PM.

The control device efficiency, as listed in Table G-5, was calculated from the change in emission factors divided by the baseline emission factors for 1) the Method 5 filter only, 2) Method 5 front half, 3) Method 5 total PM, and 4) ISO 8178. Again, there was good agreement between the control efficiencies measured by Method 5 filter only, Method 5 front half and ISO 8178, all close to 85 percent. The 75 percent reduction calculated using ARB Method 5 total PM was lower. Since all the calculated control efficiencies were lower than a projected 90 percent, the unit was inspected by the manufacturer’s technician. During the inspection, a leak was found in the seal between the ceramic filter and the housing. Upon completion of the comparison study, the leak was sealed and control efficiency increased to approximately 91 percent, based on further ISO 8178 testing.

In summary, comparisons of the D1 weighted emission factors for the two test methods indicate the following

- ARB Method 5 total PM is 2 to 4 times higher than ISO 8178 PM.
- ARB Method 5 filter only, ARB Method 5 front half and ISO 8178 levels showed good agreement.
- Measured control efficiency was lower using ARB Method 5 total PM
- Measured control efficiency was similar for ARB Method 5 filter only, ARB Method 5 front half and ISO 8178 methods.

IV. Discussion

While there are many differences in stationary source and off-road type testing, the inclusion of the condensable component may have the largest effect. While ARB Method 5 includes a condensable component, the off-road methods typically include only a filterable component. Proponents of the off-road methods argue that the stationary source methods which includes condensable PM such as ARB Method 5 overestimate the PM by including artifacts or secondary particulate formed from the interaction of particulate precursors including sulfur dioxide, sulfur trioxide, oxides of nitrogen and ammonia with water in the impinger. (England, 2000)

Proponents of stationary source methods such as ARB Method 5 argue that off-road methods underestimate condensable portion of the total PM by using sampling temperatures that are higher than ambient temperatures and by excluding secondary particulate formation that may occur in the condensable impinger portion of stationary source test methods. In addition, the off-road methods are based on dilution techniques requiring equipment that is generally limited to test bed facilities. Since stationary source engines are not portable and require compliance methods that can be performed in the field, off-road methods have not been available for stationary source testing until very recently. With the development of mobile test labs and minidilution systems, off-road dilution based methods are becoming available for field-testing, but are not widely available at this time. Also, some of the commercial minidilution systems do not have integrated exhaust flow measurement capabilities and rely on the same types of flow measurements used in stationary source testing. Precise measurement of the exhaust flow rate is essential to accurately determine the mass emission rate of the pollutant as required by most regulations.

V. Recommendations

The emission levels and control efficiencies contained in the regulation are derived from off-road engine certification and verification programs. These programs are generally based on dilution methods that include specified test cycles. Based on the results of this method comparison, the limits contained in this regulation may not be able to be met using a compliance method that contains a condensable component. As determined in this study, ARB Method 5 total PM is two to four times higher than ISO 8178 emission factors. In addition, measured control device efficiency was lower when using ARB Method 5 total PM. Other studies evaluating the condensable component have shown that particulate levels in the condensable portion are dependent on fuel sulfur levels and sampling. (England, 2000) Since total PM levels are much lower in controlled engines, required sample times can increase significantly, potentially increasing the level of secondary particulate formation. While many of these devices do require low sulfur fuel, some manufacturers are developing selective catalysts to be used with higher fuel sulfur level, which may also increase the potential for sulfate formation in the backhalf component.

In order to harmonize with certification and verification programs, staff recommend ISO 8178 as the primary test method for to demonstrate compliance with the requirements of this regulation. Since there is good agreement between the emission factors calculated from ARB Method 5 front half portion and ISO 8178 emission factors, staff recommends allowing ARB Method 5 front half (filter + probe wash) to be used as an alternative. When using ARB Method 5 front half as an alternative to ISO 8178, staff recommend using steady–state emission test cycles as outlined in ISO 8178 Part 4.

We believe that using the front half component as a measure of diesel PM emissions is consistent with the methodologies that were used to estimate diesel PM exposure concentrations in the key epidemiological studies supporting the identification of diesel PM as a toxic air contaminant. In the railroad worker study, diesel exhaust exposure was estimated using personal samplers and fixed Hi-volume samplers. (OEHHA, 1998) The high exposure group included individuals working in the close proximity to locomotives. Given the close proximity of the exposed individuals to the source of diesel exhaust emissions, we believe that the PM measured was predominately "fresh" (i.e. minutes old) diesel exhaust emissions. That is, diesel exhaust which had not undergone significant atmospheric transformation. Because the impinger catch passes the diesel exhaust through two water impingers, the PM captured in the impingers is more representative of “aged” (i.e. hours to days old) diesel exhaust. Thus, we believe that “fresh” diesel emissions are best estimated by using the front half component without counting the material collected in the impinger. Using the impinger catch may overestimate the diesel PM concentration compared to the concentrations found in the health studies. In the truck driver study, measurements of elemental carbon were used as a surrogate for diesel exhaust emissions. Elemental carbon is exclusively captured in the front half. Thus, using the front half catch without counting the material collected in the impinger is appropriate for measuring elemental carbon.

Since the key epidemiological studies focused on “fresh” diesel exhaust or elemental carbon, we believe that using the front half to estimate PM emission is consistent with the techniques used to establish diesel PM as a toxic air contaminant.

Figure G-3: MY 1991 CAT 3406B Baseline

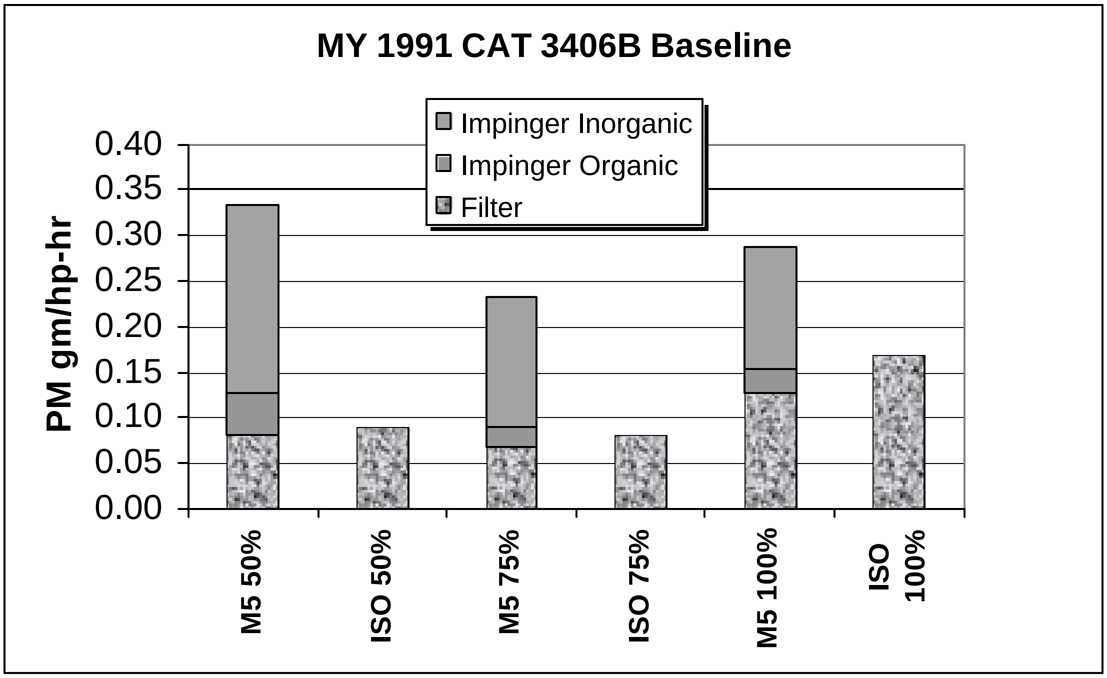


Figure G-4: MY 1991 DDC 8V 92 Baseline

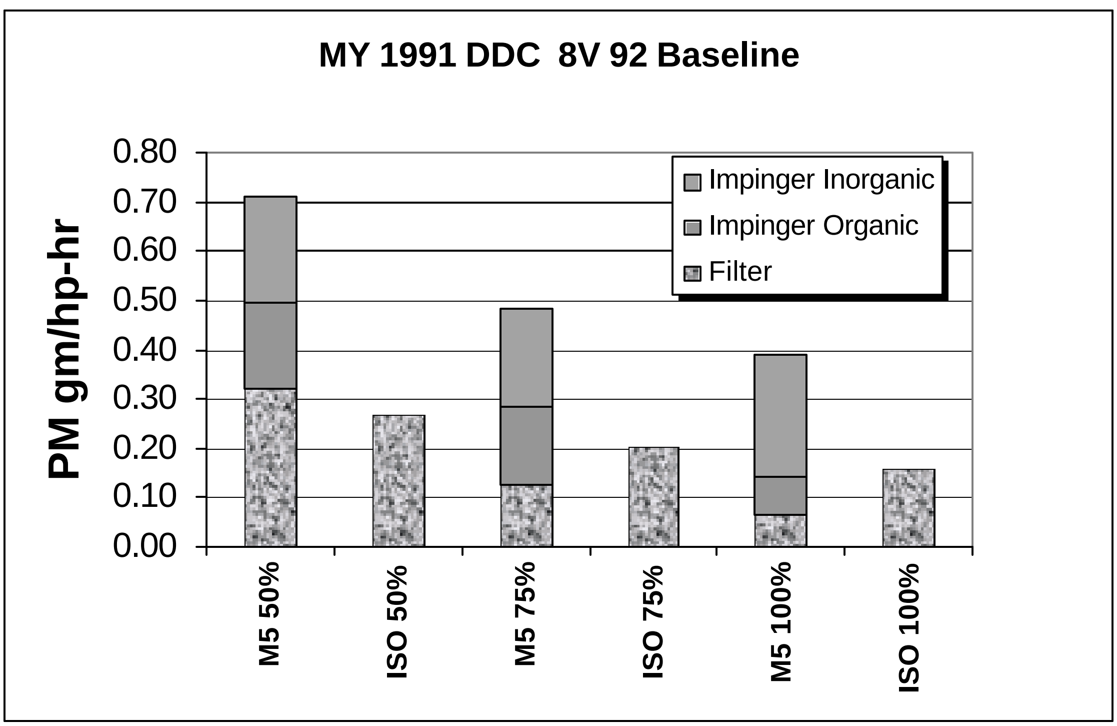


Figure G-5: MY 1999 DDC Series 60 Baseline

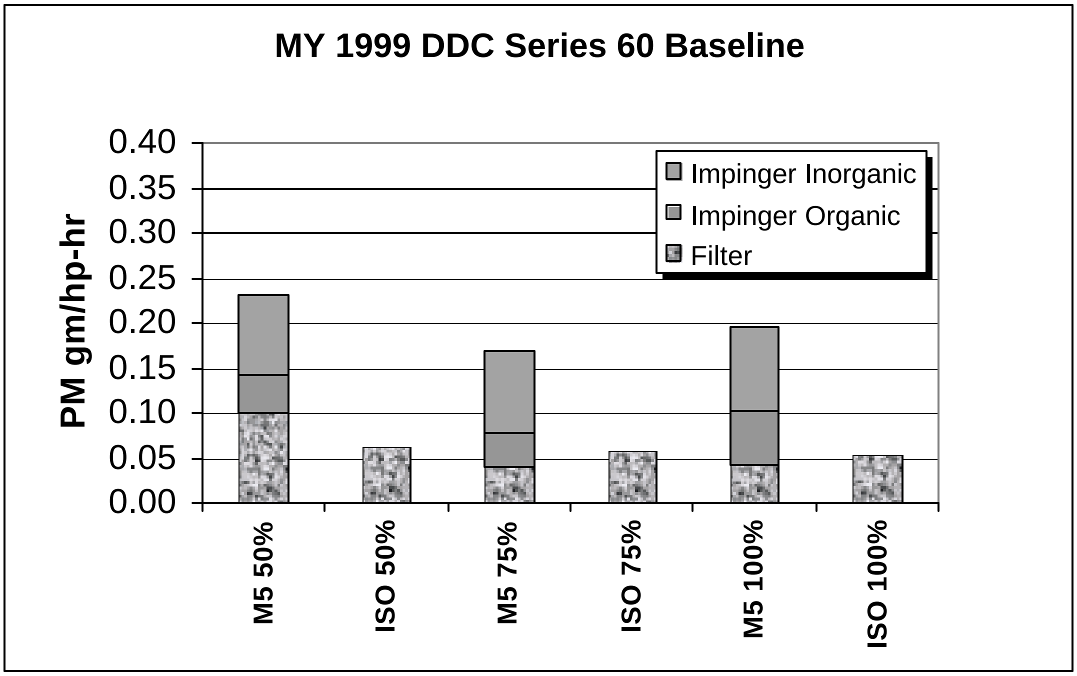


Figure G-6: MY 2000 CAT 3406C Baseline

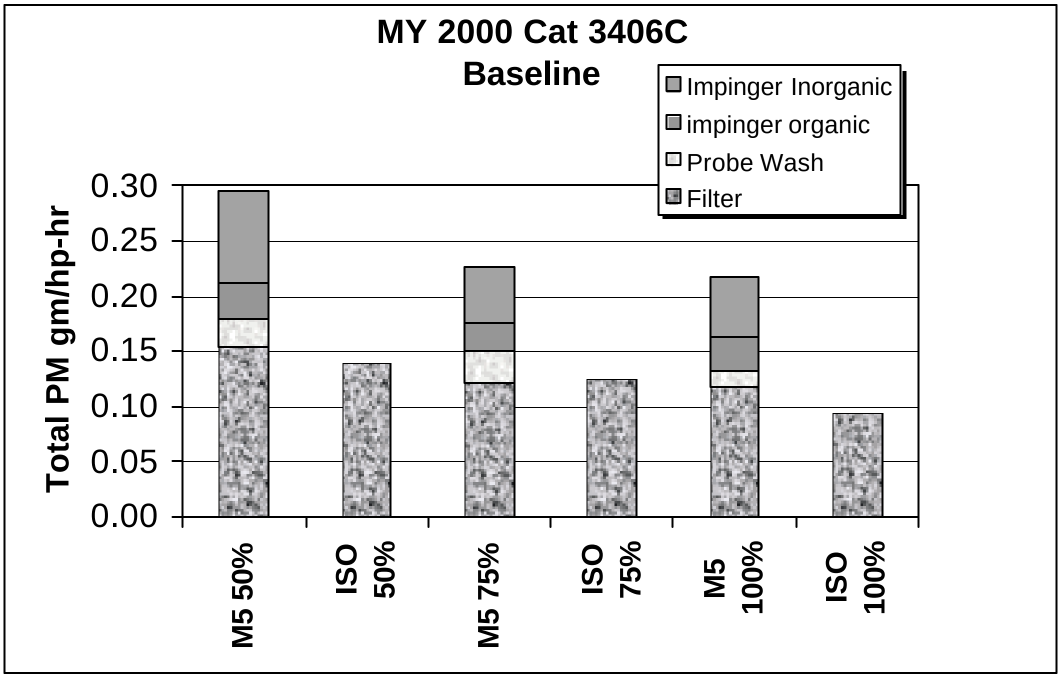
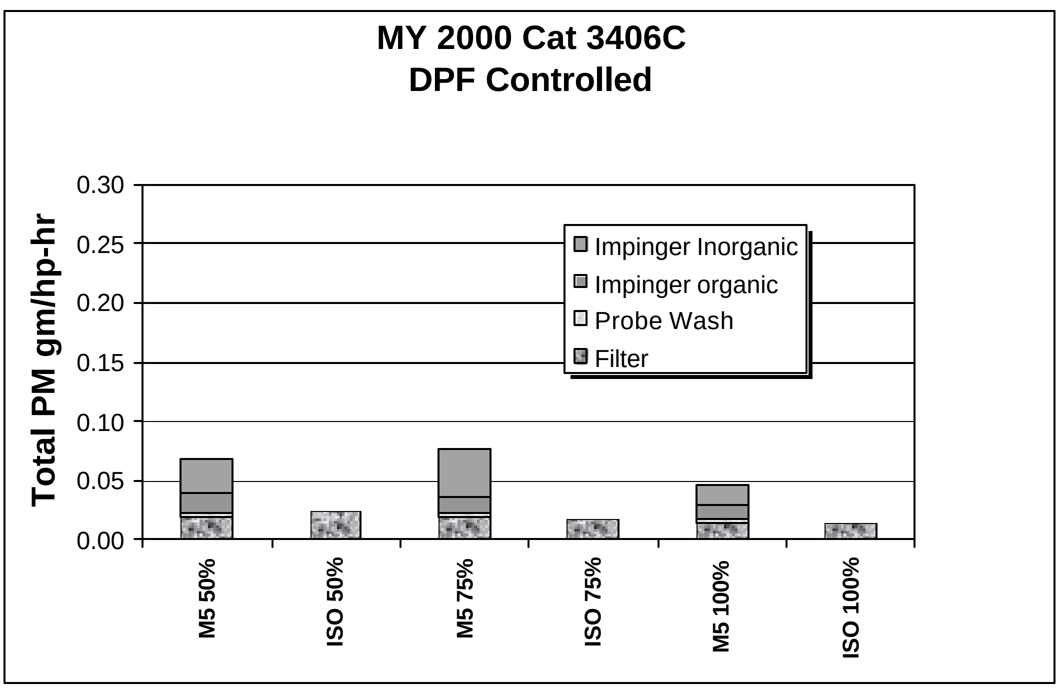


Figure G-7: MY 2000 CAT3406C DPF Controlled



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